Photovoltaic Systems Engineering

Photovoltaic System Components:

Photovoltaic generator: Photovoltaic modules which are interconnected to form a DC power producing unit, usually called an array.

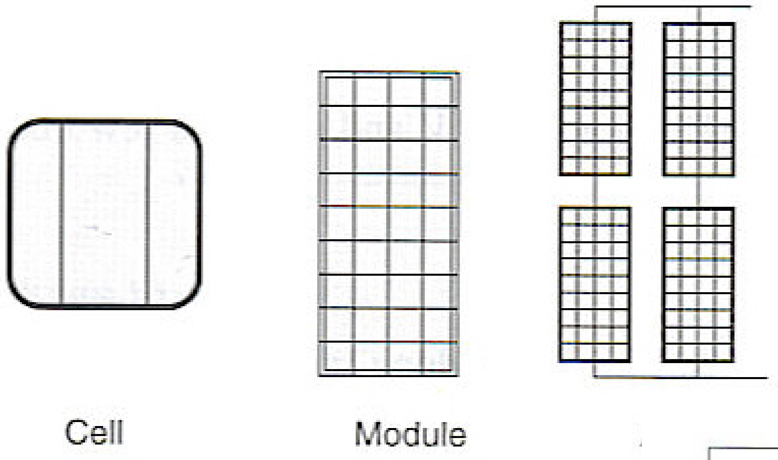
Power conditioning and control: Various electronic devices used to accommodate the variable nature of power output from the PV generator; e.g. to convert the DC power into AC output

Storage system: Stand-alone PV systems make provision for energy storage; e.g. battery storage

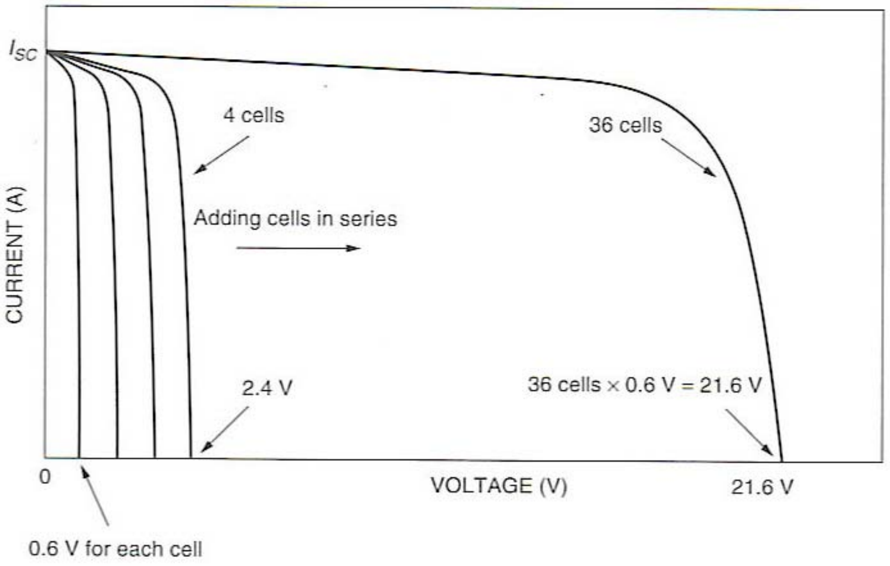
Sources: Solar Electricity, Edited by Tomas Markvart, Wiley, 2000

Photovoltaic Systems Engineering, Roger Messenger & Jerry Ventre, CRC, 2000

PV Array



For cells wired in series, their voltages at any given current add. A typical module will have 36 cells.



Source: Renewable and efficient electric power systems by Gilbert M. Masters, Wiley Interscience, 2004.

Photovoltaic Module

Typical 10 cm x 10 cm cell power: 1 - 1.5 W (under standard conditions)

Supply voltage of a single cell: 0.5 - 0.6 V

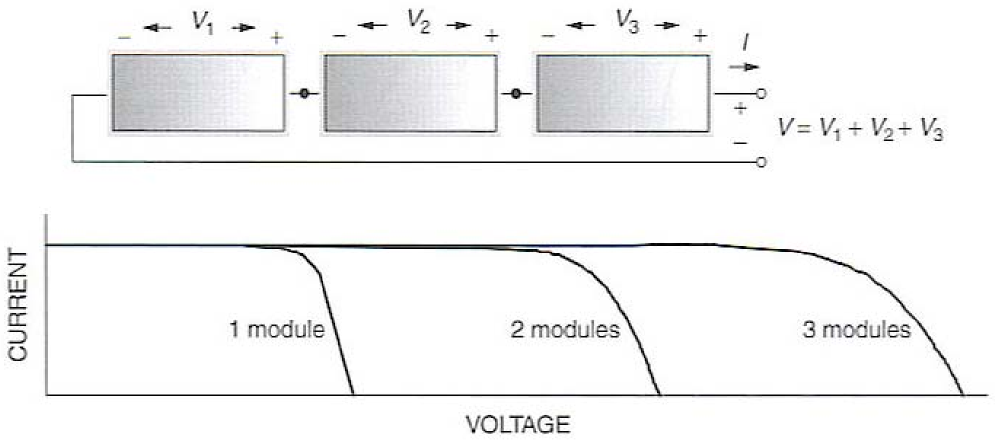
Standard conditions:

Irradiance	1000 W/m^2
Spectral distribution	AM1.5
Cell temperature	25^{o}C

Module voltage is based on a number of cells (typically 32 - 34) connected in a series (usually matched to the nominal voltage of the storage system)

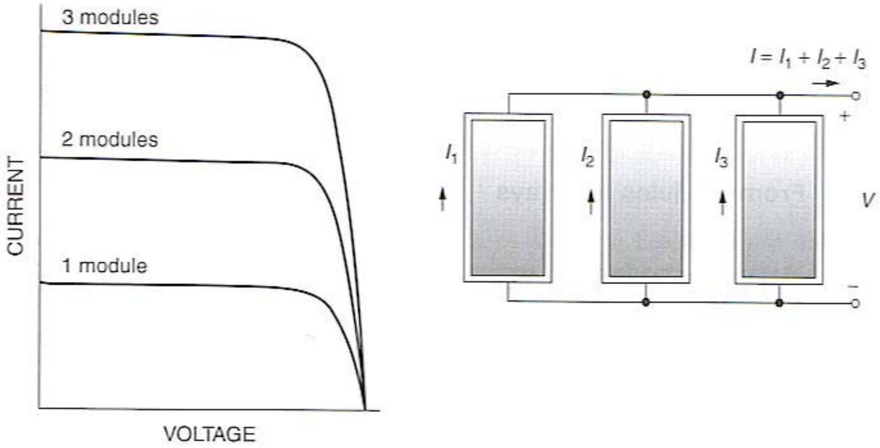
Typical module power: 40 - 60 W

Module Connectivity



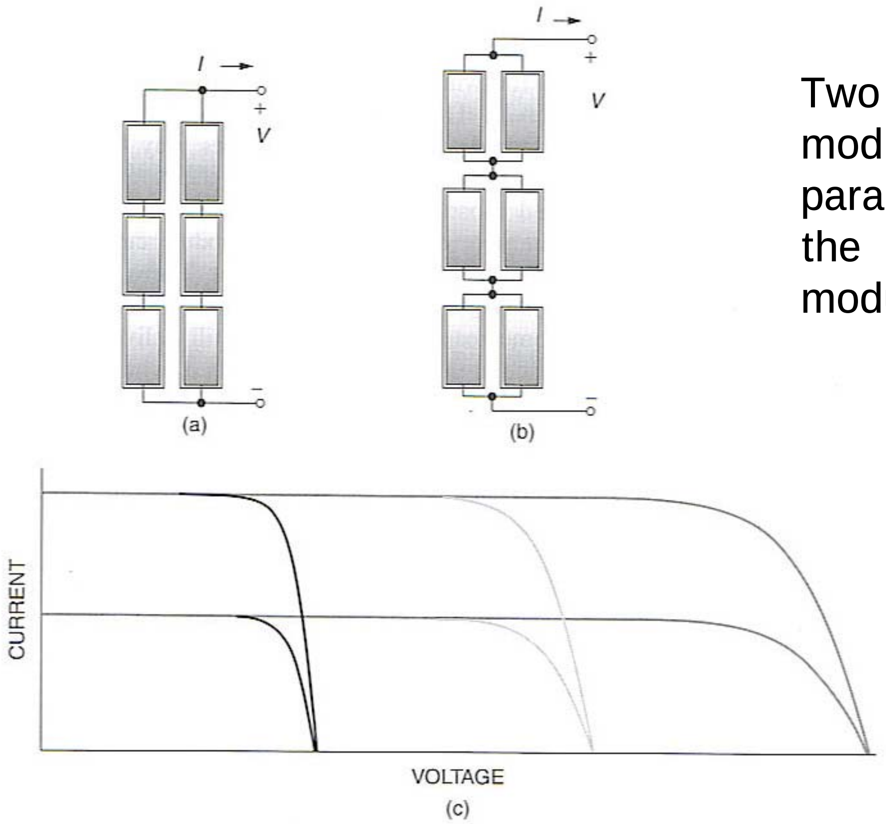
For modules in series, at any given current, voltages add.

For modules in parallel, at any given voltage, the currents add.



Source: Renewable and efficient electric power systems by Gilbert M. Masters, Wiley Interscience, 2004.

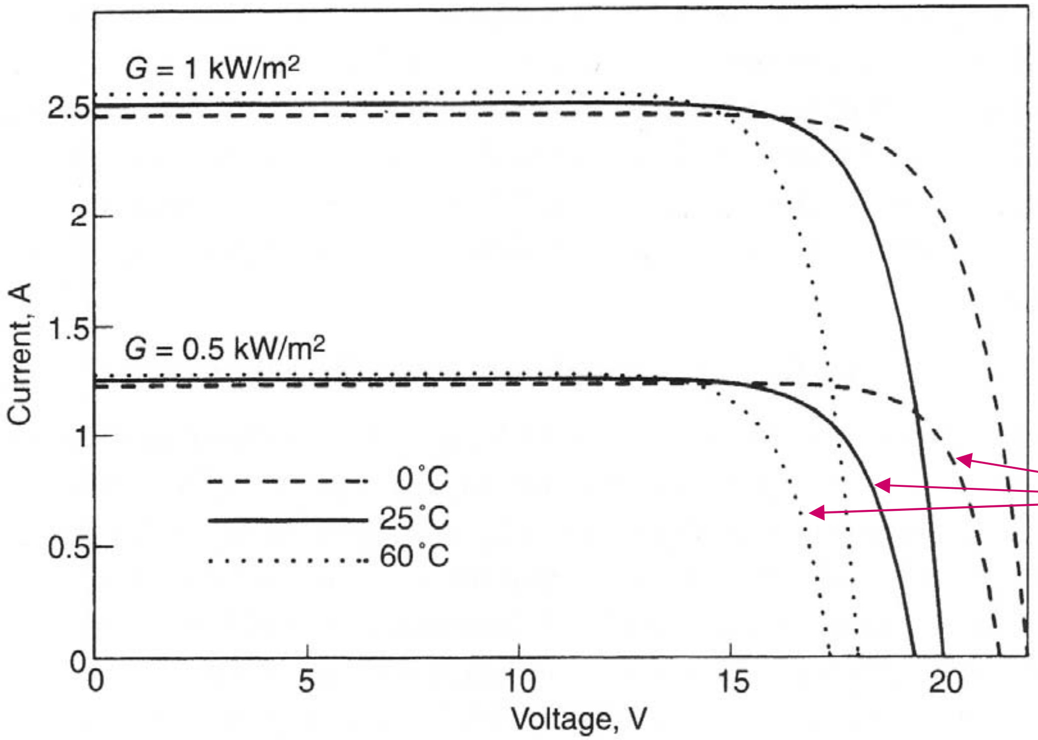
Array Arrangement



Two ways to wire an array with three modules in series and two modules in parallel. Although, the I-V curves are the same, two strings of three modules each (a) is preferred.

Source: Renewable and efficient electric power systems by Gilbert M. Masters, Wiley Interscience, 2004.

Module I-V Characteristics



Temperature Effect

Voltage variation is much less than the current drop

Effect of Temperature and Irradiance

$$\frac{dV_{oc}}{dT} = -2.3 \times n_c \,.....mV/^{o}C$$

$$\frac{dI_{sc}}{dT} = 6 \times n_c \,....\mu A/^{o}C$$

Where n_c is number of cells

$$I_{sc}(G) = (I_{sc})_{at1kW/m^2} \times G$$

G is in kW/m^2

$$V_m = 0.8 V_{oc}$$

V_m is the voltage at the MPP

Normal Operating Cell Temperature (NOCT)

It is the cell temperature when the module operates under the following conditions at open circuit:

Irradiance	800 W/m^2
Spectral distribution	AM1.5
Cell temperature	20°C
Wind speed	>1 m/s

Usually between 42 - 46°C

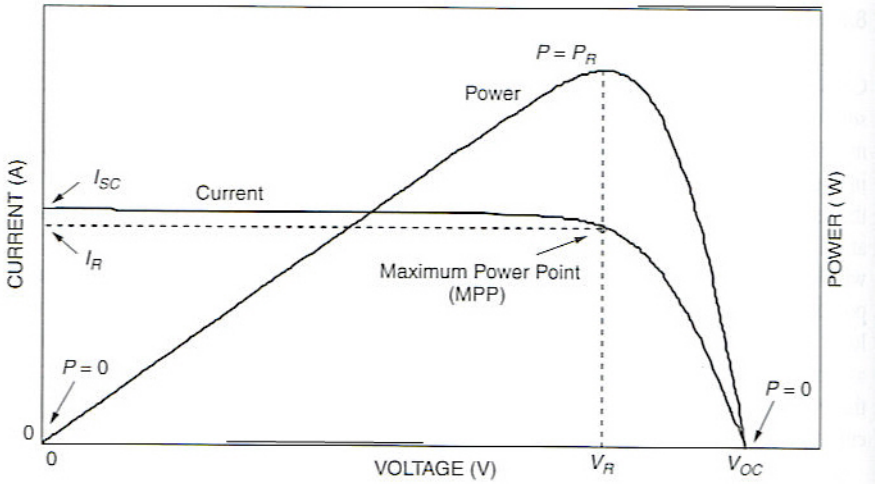
Solar Cell Temperature

(during module operation)

$$T_C - T_a = \frac{NOCT - 20}{0.8} G$$

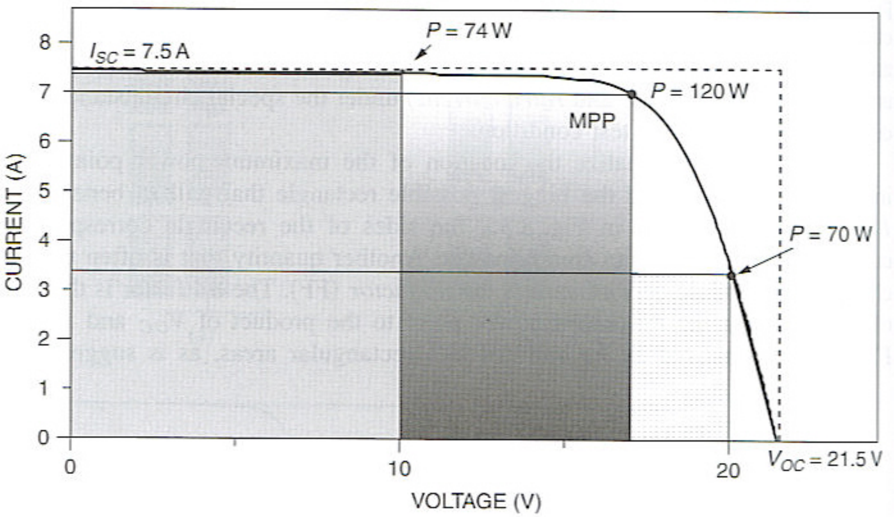
Where G is given in kW/m^2 , T$_c$ and T$_a$ are cell and ambient temperature respectively.

Maximum Power Point



At the maximum power point (MPP), the module delivers the most power that it can under the condition of sunlight and temperature.

The maximum power point (MPP), corresponds to the highest rectangle that can fit in the I-V curve. The fill factor, is the ratio of the area at MPP to the area formed by by a rectangle with sides V_{oc} and I_{sc}.



Source: Renewable and efficient electric power systems by Gilbert M. Masters, Wiley Interscience, 2004.

Battery Operation

Module - 12V Battery operation:

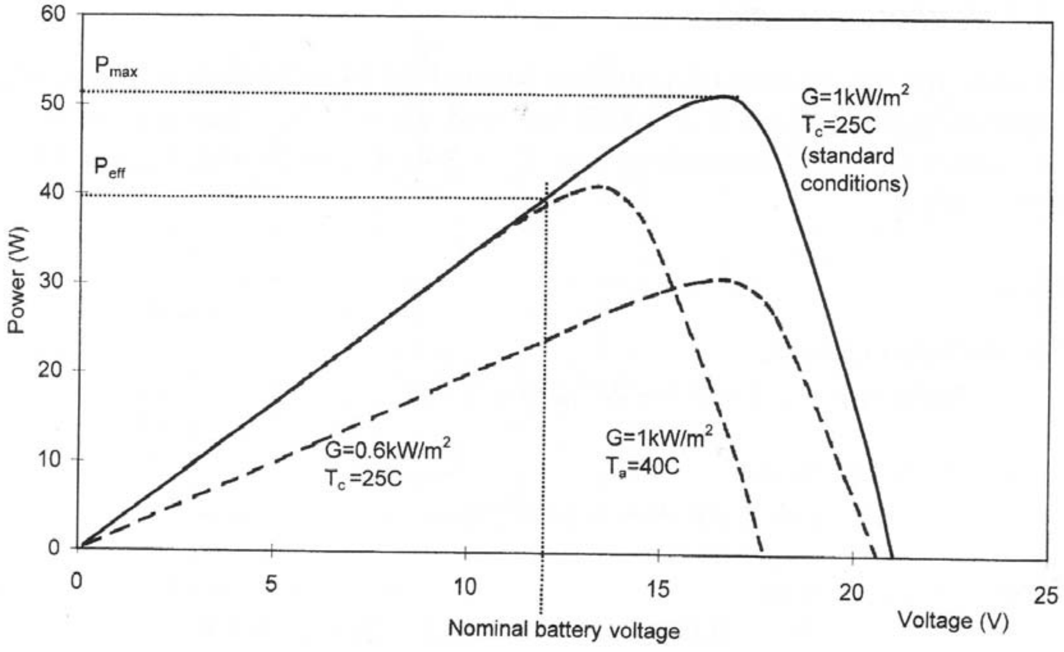


Fig. 4.5 Voltage dependence of the power produced by a PV module as a function of irradiance and cell or ambient temperature T_c or T_a

Output power P

$$P = I_{sc}(G)V_{bat} = GP_{eff}$$

$$P_{eff} = V_{bat}I_{sc}$$

Module operation with MPP tracker

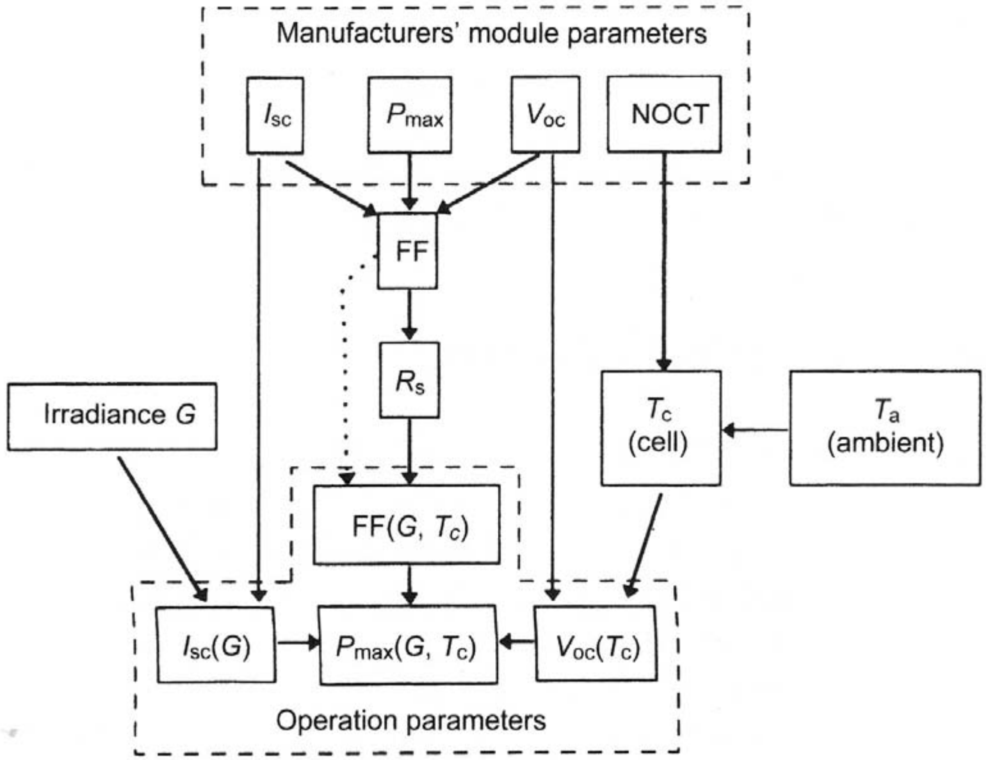


Fig. 4.6 Calculation of the module operation parameters in systems using MPP tracker

Module Parameter Determination

Example:

A module is formed by 34 solar cells in a series. The operating conditions are: G = 700 W/m^2 and T_a = 34^{o}C. The specifications under standard conditions are; I_{sc}=3A; V_{oc}=20.4V; P_{max}=45.9W, NOCT = 43^{o}C.

1. Short circuit current

   $I_{sc} = (I_{sc})_{1kW/m^2}\ G = 3 \times 0.7 = 2.1$ A

2. Solar cell temperature

   $T_C = T_a + ((NOCT - 20)/0.8)\ G = 34 + ((43-20)/0.8)\ 0.7 = 54.12^oC$

3. Open-circuit voltage

   $(V_{oc})_{at\ 54.12} = V_{oc} - 2.3\ n_c\ (T_c - T_a) = 20.4 - (2.3x34x(54.12-25)) = 18.1V$

4. Maximum power

   $P_{max} = FF\ x\ V_{oc} x\ I_{sc} = 2.1x18.1x0.75 = 28.5$ W   (62% of the nominal rating)

   FF = 45.9/(20.4x3)= 0.75

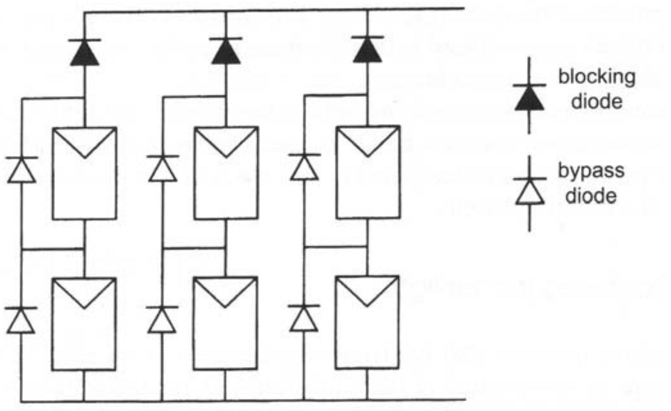
Module Interconnection

N_s : number of modules = 2

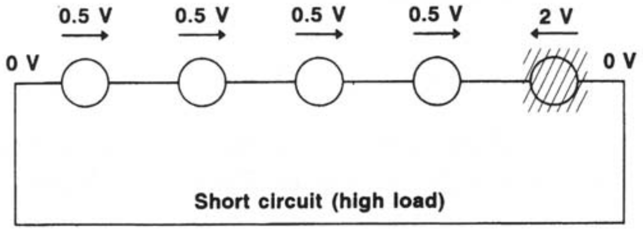
N_p : number of parallel strings = 3

N_s determines DC bus voltage

N_p determines the required current



Hot-spot formation



Isolation Diode

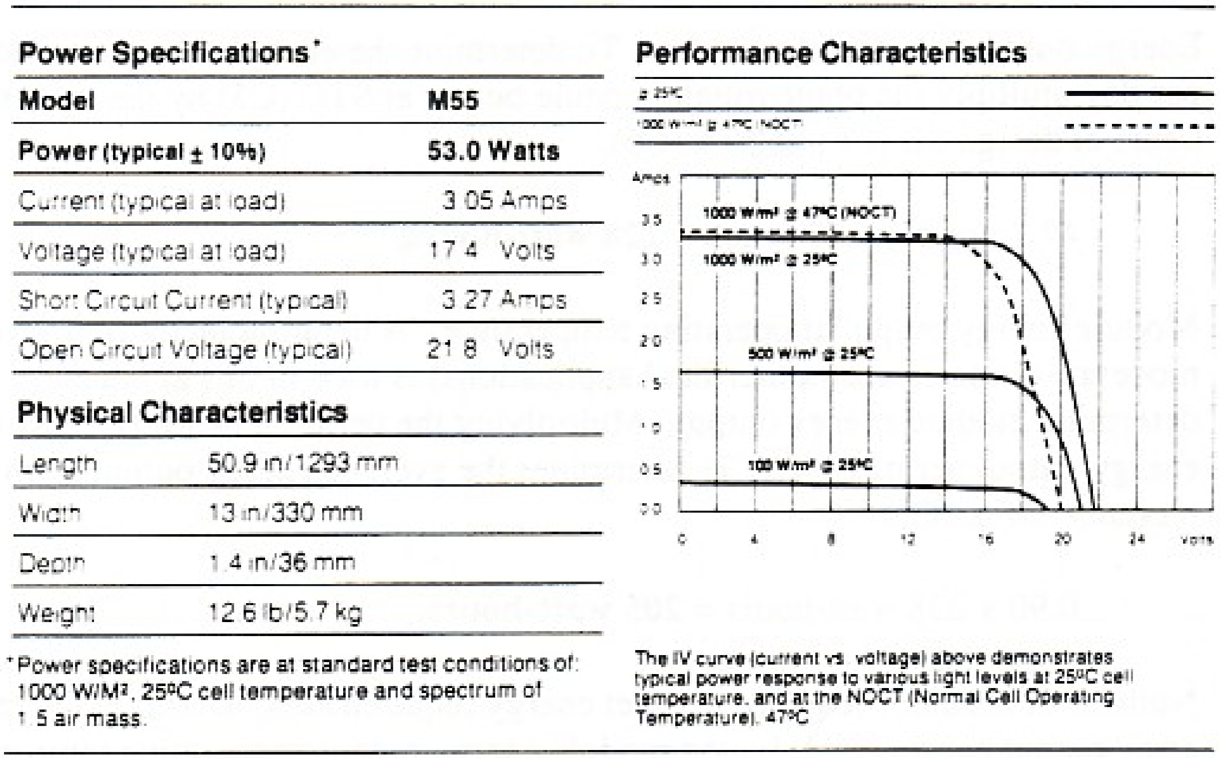
Blocking or isolation diode:

They are placed to prevent current from flowing backwards through the module. Also prevent discharge of batteries during night.

Bypass diode:

When a string of cells in series contains one bad cell or one cell shaded from the sun, an open circuit can exist in which there is no current flow. Bypass diode is used to shunt current around rather than through a group of cells or modules whenever necessary.

Module Specifications



Power Specifications*

Model	M55
Power (typical ± 10%)	53.0 Watts
Current (typical at load)	3.05 Amps
Voltage (typical at load)	17.4 Volts
Short Circuit Current (typical)	3.27 Amps
Open Circuit Voltage (typical)	21.8 Volts

Physical Characteristics

Length	50.9 in/1293 mm
Width	13 in/330 mm
Depth	1.4 in/36 mm
Weight	12.6 lb/5.7 kg

*Power specifications are at standard test conditions of: 1000 W/M², 25°C cell temperature and spectrum of 1.5 air mass.

Performance Characteristics

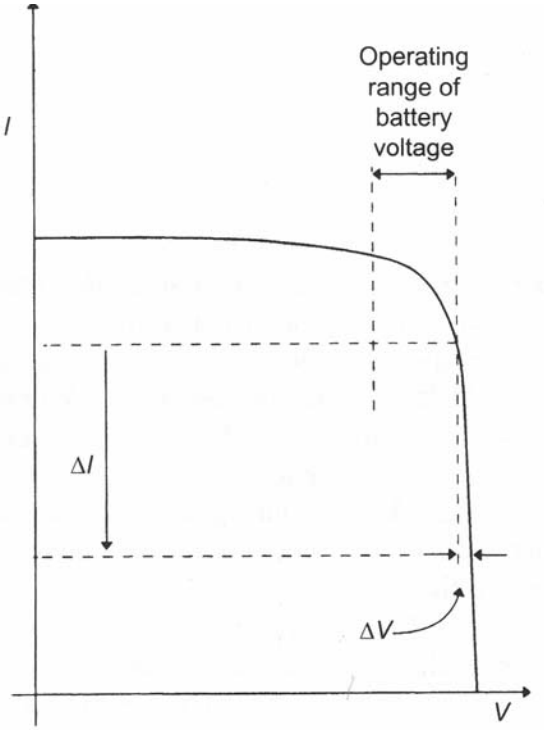
@ 25°C	━━━━
1000 W/m² @ 47°C (NOCT)	- - - - -

The IV curve (current vs. voltage) above demonstrates typical power response to various light levels at 25°C cell temperature, and at the NOCT (Normal Cell Operating Temperature), 47°C

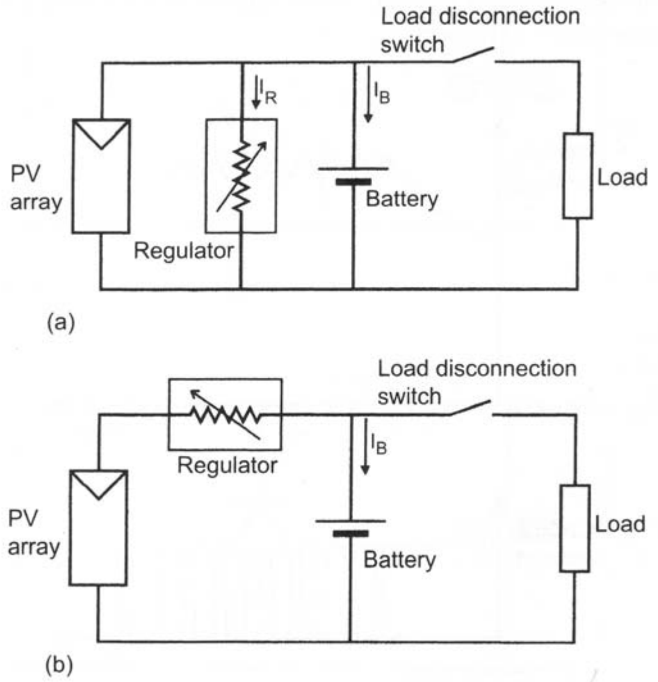
Figure 6.10 Siemens Solar M-55 module specifications

Power Conditioning and Control

Charge regulator:



The operation of self-regulating PV system



(a) Shunt regulator; (b) series regulator

Power Conditioning and Control

Switching DC/DC Converters:

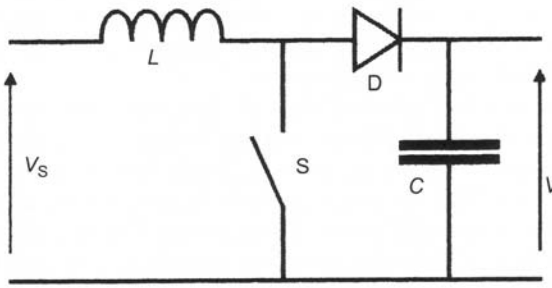


Fig. B4.1 Circuit diagram of the buck converter

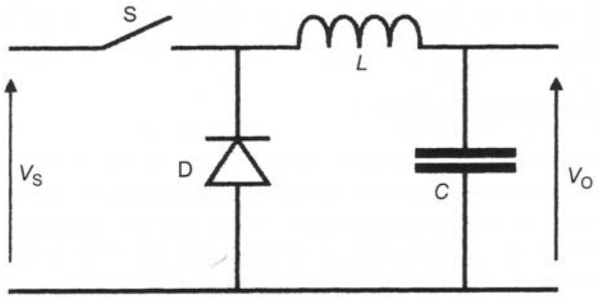


Fig. B4.2 Circuit diagram of the boost converter

Reduces the voltage

D: duty ratio

Increases the voltage

Power Conditioning and Control

DC/DC Converter: MPP tracker

$$V_R = \sqrt{P_{\max} R}$$

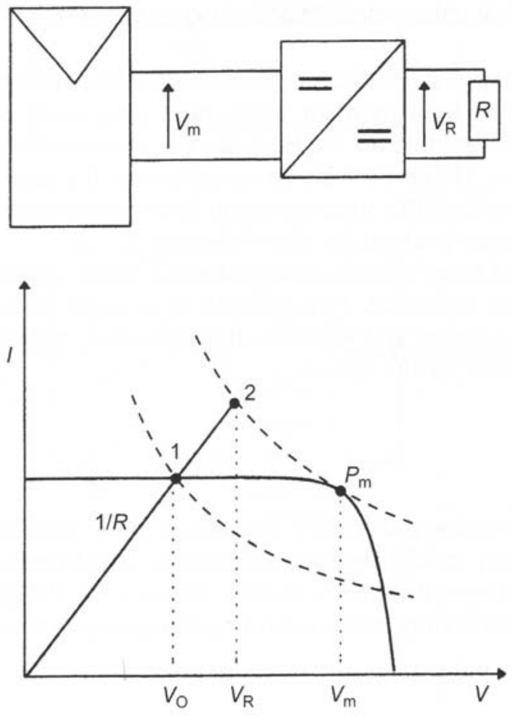


Fig. 4.19 The operation of MPP tracker (after E. Lorenzo, Electricidad Solar Fotovoltaica, Publication of E.T.S.I. Telecommunicacion, Madrid, 1984)

Power Conditioning and Control

Inverters from DC to AC:

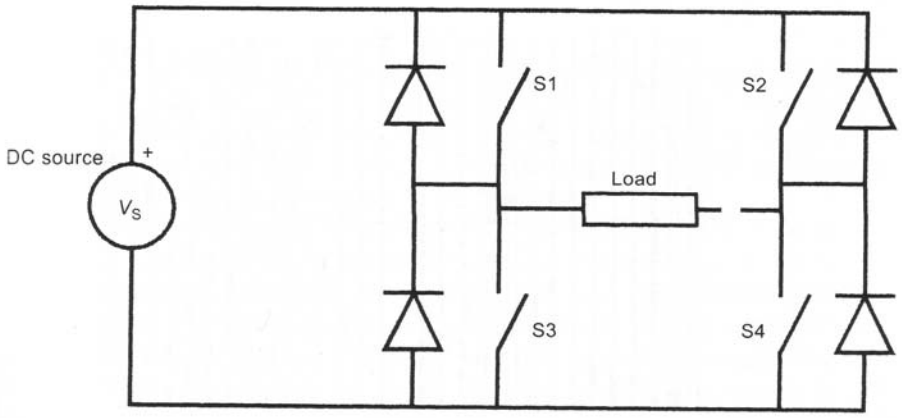
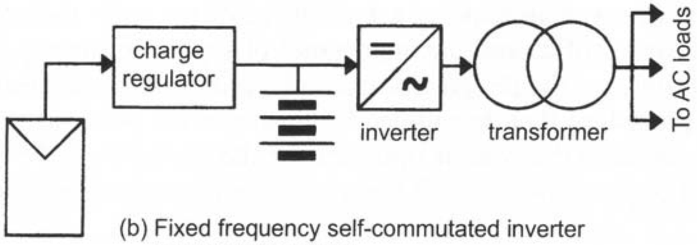
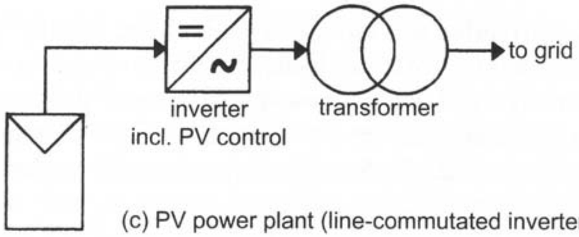


Fig. B4.3 A single-phase full bridge inverter



(b) Fixed frequency self-commutated inverter system with battery



(c) PV power plant (line-commutated inverter)

The power conditioning and control equipment makes it possible to convert the generated DC power to AC, protect the battery against the overcharge or discharge and optimize the energy transfer between the PV generator and the load.

Sizing

Sizing the photovoltaic systems:

1. Obtain the site radiation data
2. Obtain the data for typical loads

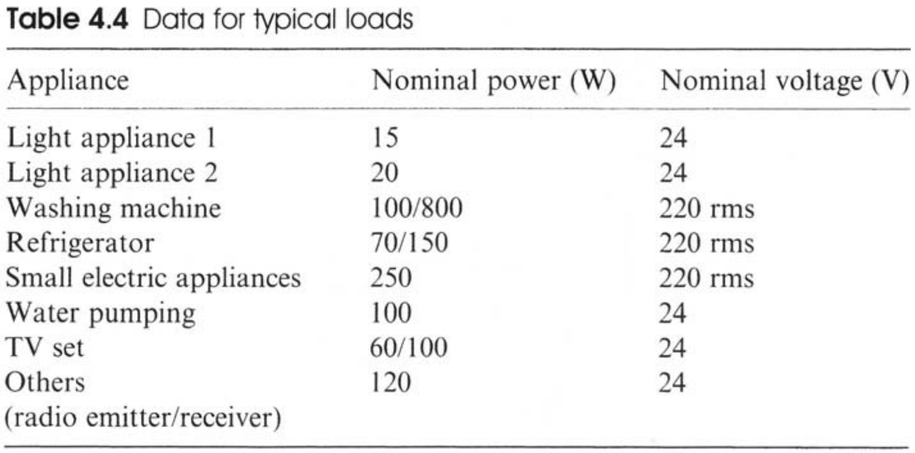


Table 4.4 Data for typical loads

Appliance	Nominal power (W)	Nominal voltage (V)
Light appliance 1	15	24
Light appliance 2	20	24
Washing machine	100/800	220 rms
Refrigerator	70/150	220 rms
Small electric appliances	250	220 rms
Water pumping	100	24
TV set	60/100	24
Others (radio emitter/receiver)	120	24

The System Energy Balance

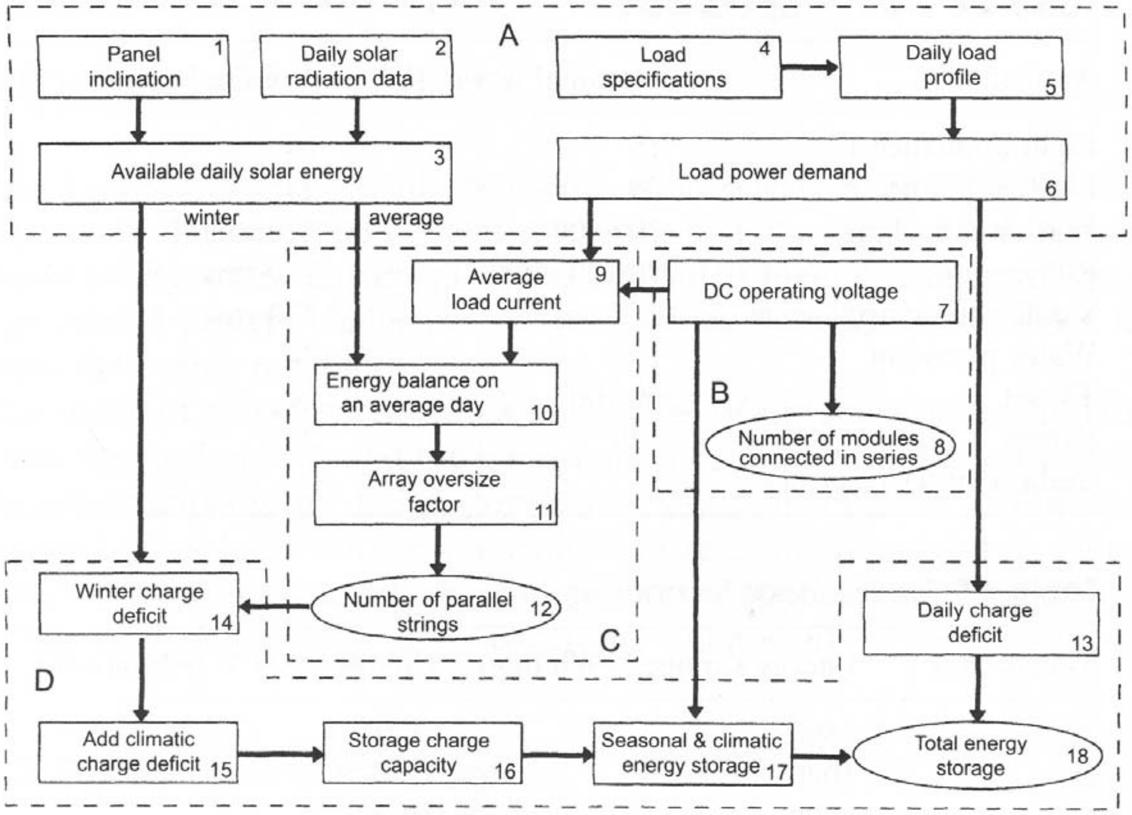


Fig. 4.21 Sizing procedure based on energy balance

The System Energy Balance

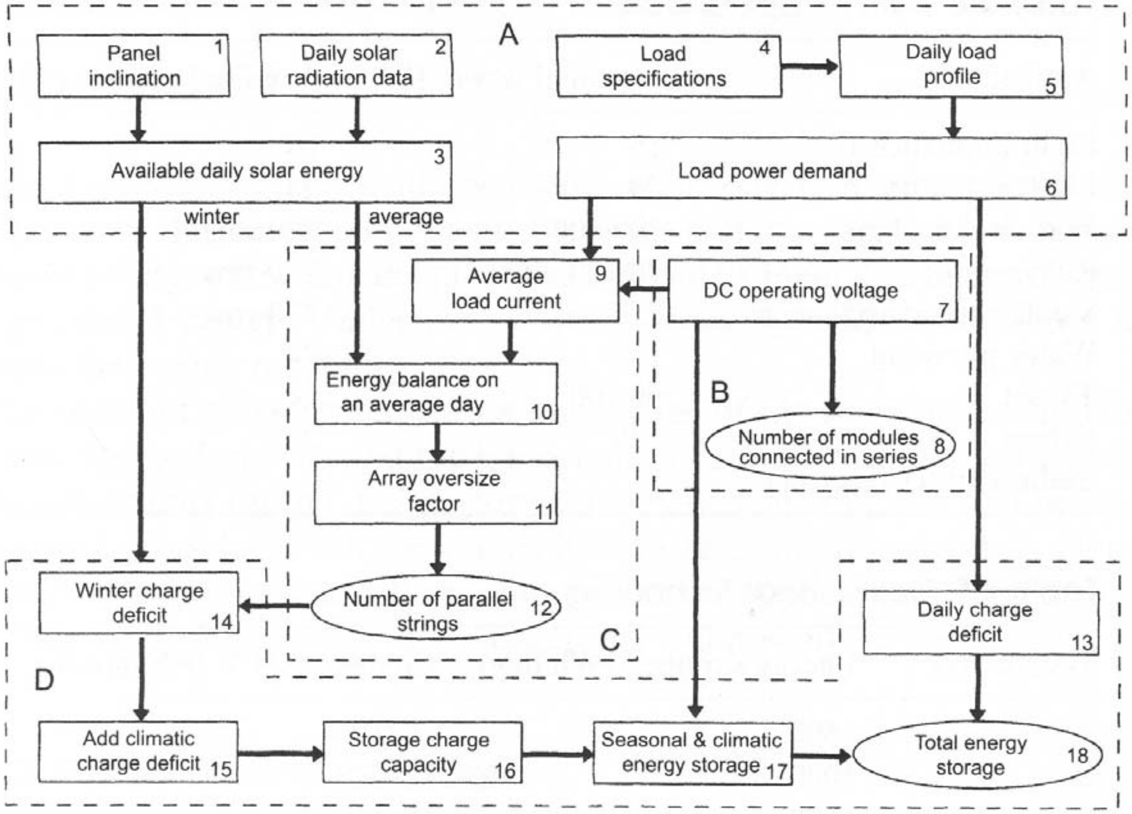


Fig. 4.21 Sizing procedure based on energy balance

Photovoltaic Systems Engineering

1. Input to the sizing procedure:

   a) Determination of the energy input - the incident solar radiation on the panel for a typical day in every month of the year.

   b) Determination of the load demand - the load profile should be determined by estimating the times when various appliances will be needed.

2. Number of series-connected modules

   a) The DC operating voltage of the system V_{DC} must be specified.

   b) The number of modules N_s is determined from

$$N_s = \frac{V_{DC}}{V_m}$$

where V_m is the operating voltage of one module

Photovoltaic Systems Engineering

3. The number of parallel strings, N_p

This number is directly related to the current requirement of the load.

a) The equivalent load current is calculated from the following equation,

$$I_L = \frac{E_L}{24V_{DC}}$$

where E_L (Wh/day) is the typical power requirement of the day.

b) Nominal current I_{PV} is defined by the AM1.5 radiation at 1kW/m^2.

$$E_L = I_{PV} V_{DC} (PSH)$$

where *PSH* is *peak solar hours, equal to the number of hours of the standard irradiance (1kW/m*^{2}*) which would produce the same irradiation.*

Photovoltaic Systems Engineering

The average load current multiplied by the number of hours in a day = the nominal current of the PV generator multiplied by the number of peak solar hours

$$I_{PV} = \frac{24 I_L}{PSH}$$

The nominal current is equal to the short-circuit current, I_{sc}

c) The number of modules connected in parallel is then given by

$$N_p = SF \frac{I_{PV}}{I_{SC}}$$

where SF is the sizing factor

Photovoltaic Systems Engineering

4. Sizing of the storage subsystem

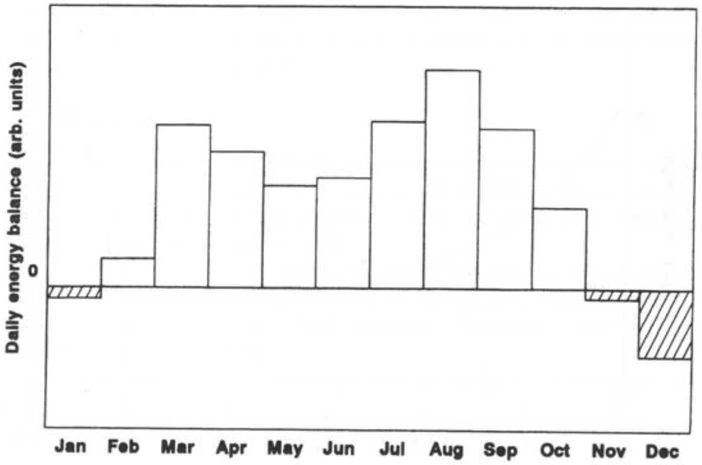
a) The daily and seasonal charge deficits calculation

The winter energy deficit, ΔE is given by

$$Q_{yd} = \frac{\Delta E}{V_{DC}}$$

where Q_{yd} is the charge deficit in ampere-hours.

This energy deficit depends on the choice of the array sizing factor SF



4.22 The daily energy balance of a stand-alone PV system

b) A further climatic charge deficit is also added to allow for a number of days of operation without energy input (lack of sunshine)

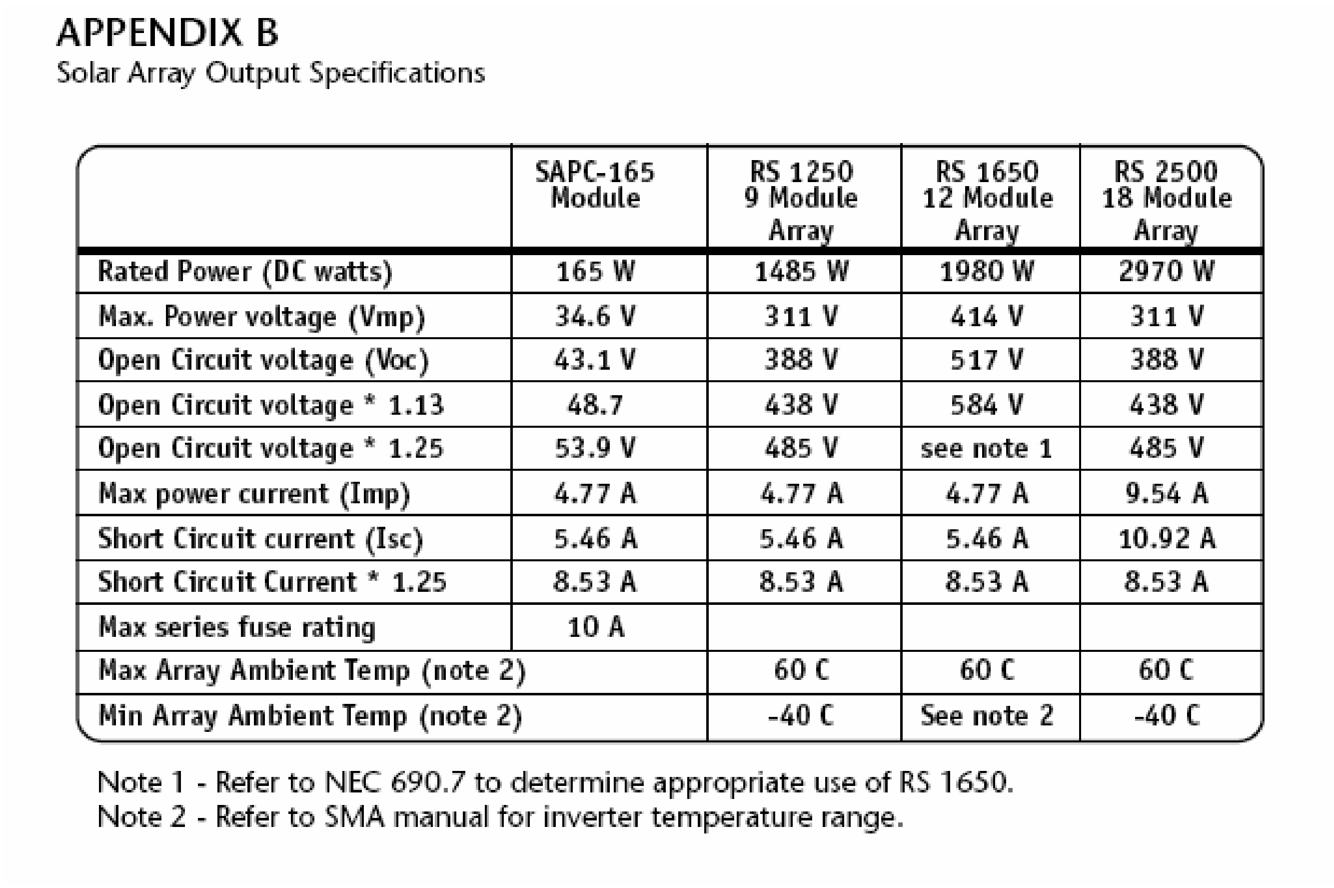
Photovoltaic Systems Engineering

Sizing of stand-alone photovoltaic system:

Point-sizing approach method: It is designed to meet the load under worst case isolation conditions, usually in the winter months for the northern hemisphere.

Reference: Photovoltaic System Design Course manual by Florida Solar Energy Center, Cape Canaveral, Florida

COE PV Array Characteristics



APPENDIX B

Solar Array Output Specifications

	SAPC-165 Module	RS 1250 9 Module Array	RS 1650 12 Module Array	RS 2500 18 Module Array
Rated Power (DC watts)	165 W	1485 W	1980 W	2970 W
Max. Power voltage (Vmp)	34.6 V	311 V	414 V	311 V
Open Circuit voltage (Voc)	43.1 V	388 V	517 V	388 V
Open Circuit voltage * 1.13	48.7	438 V	584 V	438 V
Open Circuit voltage * 1.25	53.9 V	485 V	see note 1	485 V
Max power current (Imp)	4.77 A	4.77 A	4.77 A	9.54 A
Short Circuit current (Isc)	5.46 A	5.46 A	5.46 A	10.92 A
Short Circuit Current * 1.25	8.53 A	8.53 A	8.53 A	8.53 A
Max series fuse rating	10 A			
Max Array Ambient Temp (note 2)		60 C	60 C	60 C
Min Array Ambient Temp (note 2)		-40 C	See note 2	-40 C

Note 1 - Refer to NEC 690.7 to determine appropriate use of RS 1650.
Note 2 - Refer to SMA manual for inverter temperature range.

Grid-connected Photovoltaic Systems

Energy storage is not necessary in this case

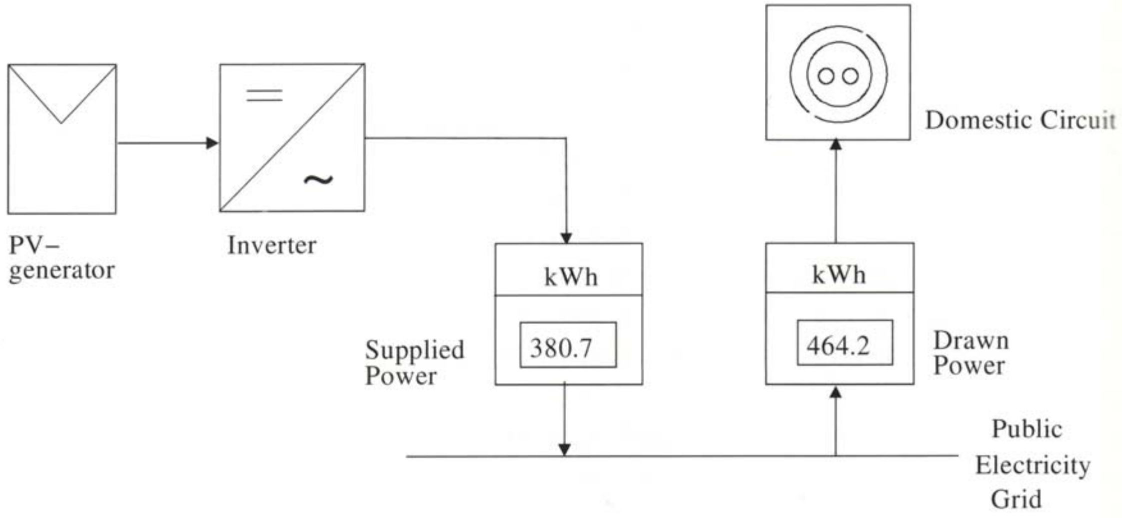


Fig. 2.35. Block diagram of a grid-connected photovoltaic generator. The location of the two energy meters may vary, depending on the adopted payment scheme

PV Industrialization

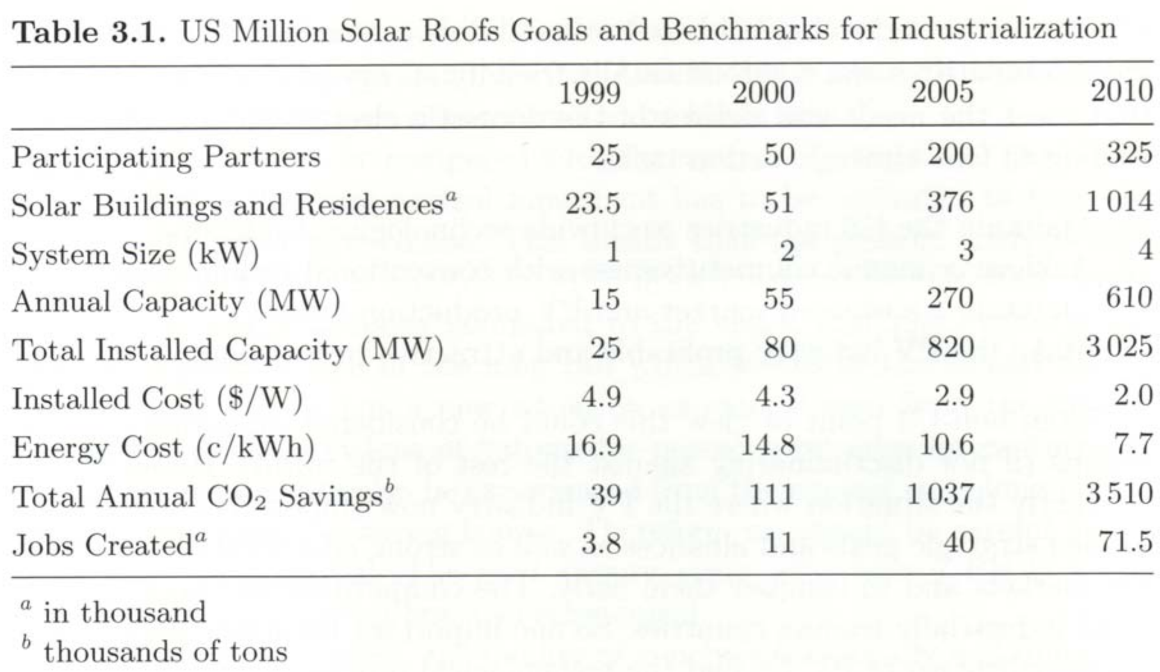


Table 3.1. US Million Solar Roofs Goals and Benchmarks for Industrialization

	1999	2000	2005	2010
Participating Partners	25	50	200	325
Solar Buildings and Residences[a]	23.5	51	376	1 014
System Size (kW)	1	2	3	4
Annual Capacity (MW)	15	55	270	610
Total Installed Capacity (MW)	25	80	820	3 025
Installed Cost ($/W)	4.9	4.3	2.9	2.0
Energy Cost (c/kWh)	16.9	14.8	10.6	7.7
Total Annual CO_2 Savings[b]	39	111	1 037	3 510
Jobs Created[a]	3.8	11	40	71.5

[a] in thousand
[b] thousands of tons

Large Scale PV Projects

SAN FRANCISCO SOLAR POWER, USA

In 2001, two proposals to install renewable energy systems in San Francisco were ratified. Construction of a 50MW solar power facility is due to begin in Spring 2003. This will come from 140-250 photovoltaic acres of panels on commercial, residential and government rooftops. Another 10-12MW of solar power will come from an agreement linked to 30MW of wind power and costing $100 million. This involves photovoltaic panels being fixed to city facilities and buildings. Together, these two propositions will provide electricity for 60,000 homes in San Francisco.

The plant will be six times larger than the world's largest solar facility, Sacramento Municipal Utility District, and will feed power directly into the network.

The plan will cut greenhouse emissions from the area by around 1%, and provide 10% of the city's electricity in the daytime, and 5% at night (peak load). The 'peaker' plant will be designed, built, operated, maintained and transferred by Local Power through an agreement with California Power Authority.

Cost of PV generated Energy

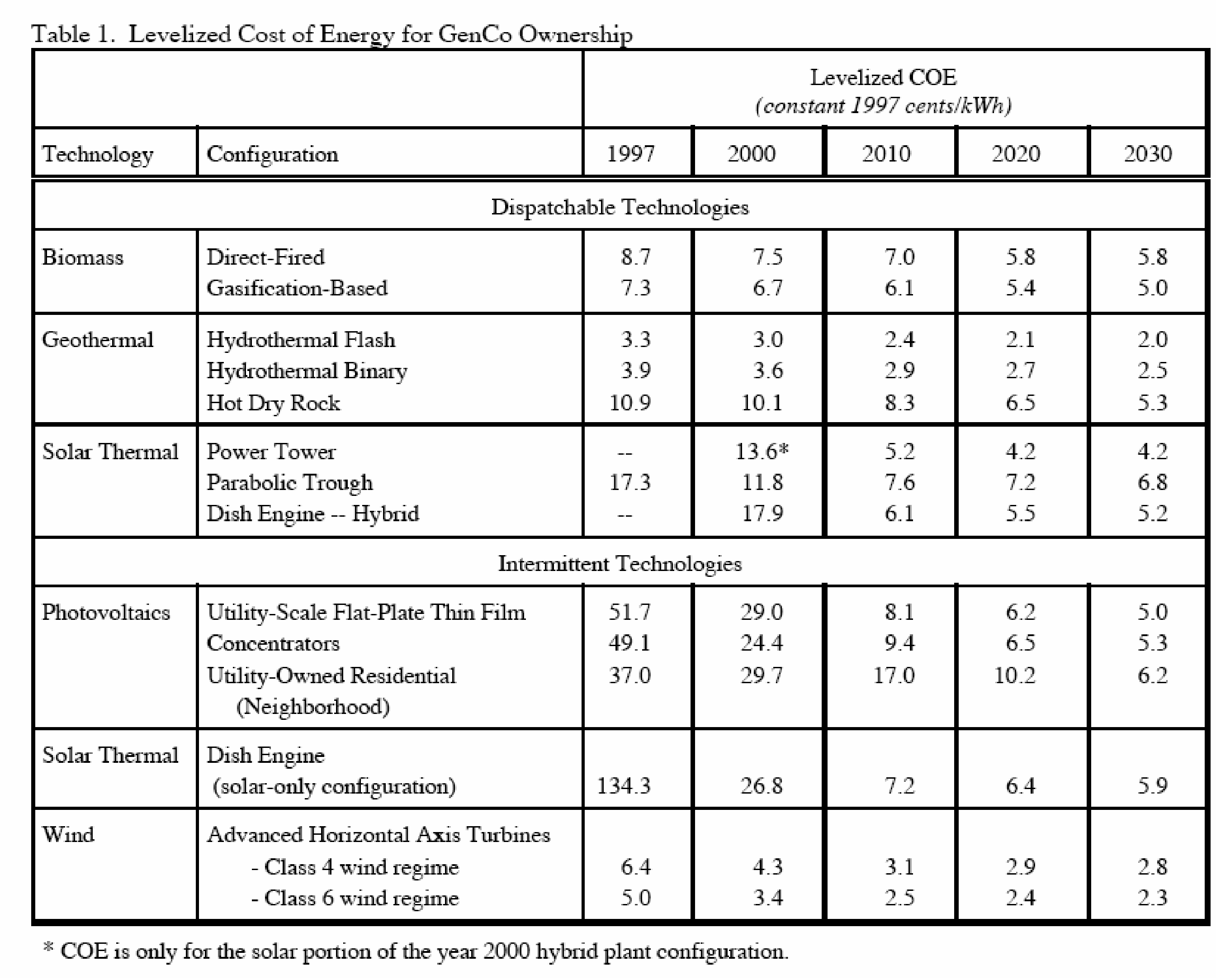
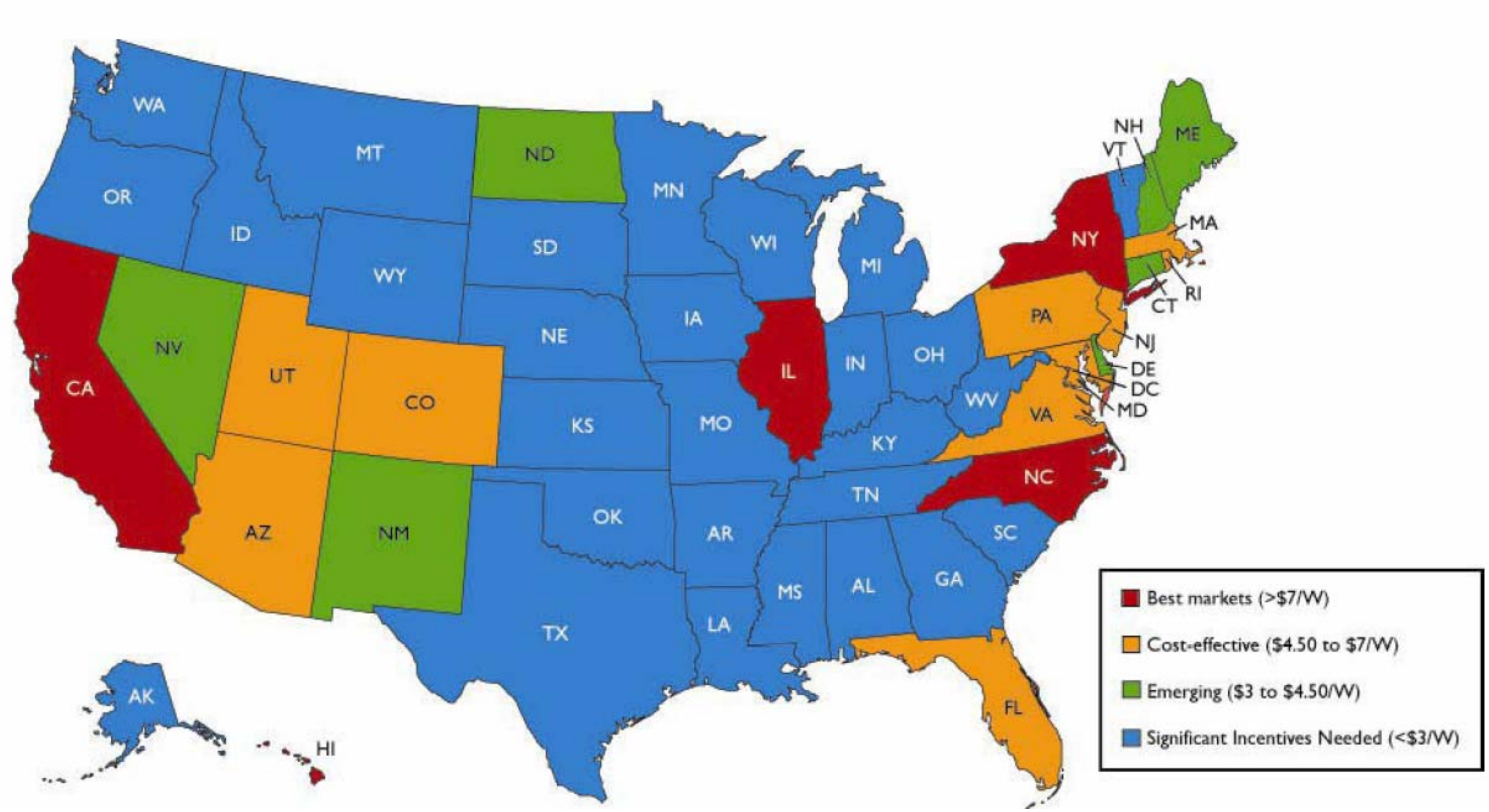


Table 1. Levelized Cost of Energy for GenCo Ownership

		Levelized COE *(constant 1997 cents/kWh)*				
Technology	Configuration	1997	2000	2010	2020	2030
Dispatchable Technologies						
Biomass	Direct-Fired	8.7	7.5	7.0	5.8	5.8
	Gasification-Based	7.3	6.7	6.1	5.4	5.0
Geothermal	Hydrothermal Flash	3.3	3.0	2.4	2.1	2.0
	Hydrothermal Binary	3.9	3.6	2.9	2.7	2.5
	Hot Dry Rock	10.9	10.1	8.3	6.5	5.3
Solar Thermal	Power Tower	--	13.6*	5.2	4.2	4.2
	Parabolic Trough	17.3	11.8	7.6	7.2	6.8
	Dish Engine -- Hybrid	--	17.9	6.1	5.5	5.2
Intermittent Technologies						
Photovoltaics	Utility-Scale Flat-Plate Thin Film	51.7	29.0	8.1	6.2	5.0
	Concentrators	49.1	24.4	9.4	6.5	5.3
	Utility-Owned Residential (Neighborhood)	37.0	29.7	17.0	10.2	6.2
Solar Thermal	Dish Engine (solar-only configuration)	134.3	26.8	7.2	6.4	5.9
Wind	Advanced Horizontal Axis Turbines					
	- Class 4 wind regime	6.4	4.3	3.1	2.9	2.8
	- Class 6 wind regime	5.0	3.4	2.5	2.4	2.3

* COE is only for the solar portion of the year 2000 hybrid plant configuration.

Cost effectiveness



Source: Solar Electric Power Association

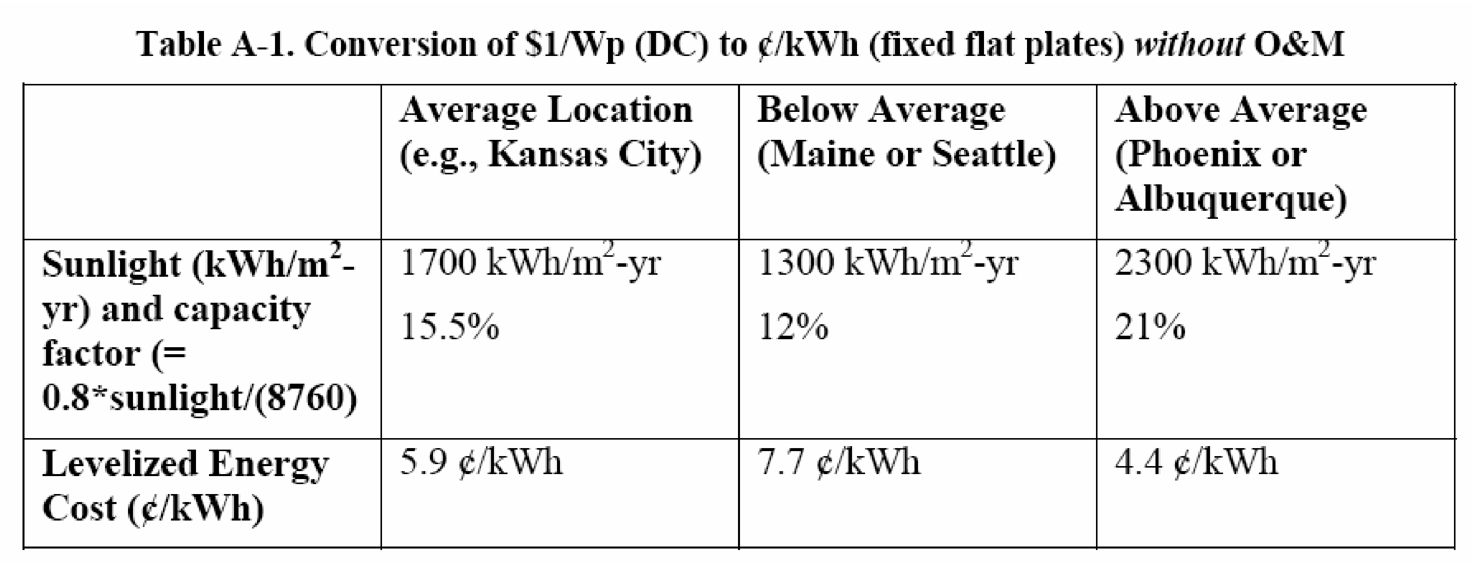


Table A-1. Conversion of $1/Wp (DC) to ¢/kWh (fixed flat plates) *without* O&M

	Average Location (e.g., Kansas City)	Below Average (Maine or Seattle)	Above Average (Phoenix or Albuquerque)
Sunlight (kWh/m^2-yr) and capacity factor (= 0.8*sunlight/(8760)	1700 kWh/m^2-yr 15.5%	1300 kWh/m^2-yr 12%	2300 kWh/m^2-yr 21%
Levelized Energy Cost (¢/kWh)	5.9 ¢/kWh	7.7 ¢/kWh	4.4 ¢/kWh